



Pistone, M., Blundy, J., & Brooker, R. A. (2017). Water transfer during magma mixing events: Insights into crystal mush rejuvenation and melt extraction processes. *American Mineralogist*, 102(4), 766-776.
<https://doi.org/10.2138/am-2017-5793>

Peer reviewed version

Link to published version (if available):
[10.2138/am-2017-5793](https://doi.org/10.2138/am-2017-5793)

[Link to publication record in Explore Bristol Research](#)
PDF-document

This is the author accepted manuscript (AAM). The final published version (version of record) is available online via Mineralogical Society of America at <http://ammin.geoscienceworld.org/content/102/4/766>. Please refer to any applicable terms of use of the publisher.

University of Bristol - Explore Bristol Research

General rights

This document is made available in accordance with publisher policies. Please cite only the published version using the reference above. Full terms of use are available:
<http://www.bristol.ac.uk/pure/about/ebr-terms>

1 **WATER TRANSFER DURING MAGMA MIXING EVENTS:**
2 **INSIGHTS INTO CRYSTAL MUSH REJUVENATION AND**
3 **MELT EXTRACTION PROCESSES**

4 Mattia Pistone ^{1,2,*}, Jon Blundy ¹, Richard A. Brooker ¹, EIMF ³

5 1) *School of Earth Sciences, University of Bristol, Wills Memorial Building, Queen's Road, BS8 1RJ,*
6 *Bristol, United Kingdom.*

7 2) *Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution,*
8 *10th Street & Constitution Avenue NW, Washington, DC 20560-0119, United States.*

9 3) *Edinburgh Ion Microprobe Facility, School of Geosciences, University of Edinburgh, Grant*
10 *Institute, Kings Buildings, West Mains Road, EH9 3JW, Edinburgh, United Kingdom.*

11 * *Now at Institute of Earth Sciences, University of Lausanne (UNIL), Bâtiment Géopolis, Office 3430,*
12 *Quartier UNIL-Mouline, CH-1015, Lausanne, Canton of Vaud, Switzerland.*

13

14 **Abstract**

15 Many plutons preserve evidence of magma mixing between hydrous mafic
16 magmas and resident felsic crystal-rich mushes. To investigate water transfer
17 processes in such systems following thermal equilibration, we conducted 24-hour
18 experiments to establish the petrological evolution of a water-undersaturated (4 wt%
19 H₂O in the interstitial melt) quartz-bearing dacite crystal mush (0.5-0.8 in crystal
20 fraction) intruded by a water-saturated (≥ 6 wt% H₂O), initially crystal-free, andesite
21 magma at 950 °C and 4 kbar (12 km depth). Our results show isothermal
22 undercooling resulting from a change in liquidus temperatures of the interacting
23 magmas due to their changing water content. Specifically, mafic samples dramatically
24 crystallise during water escape into the felsic end-members and consequent increase
25 in liquidus temperature. Conversely, the addition of water to the felsic mush reduces
26 the liquidus temperature, leading to an increase in melt fraction. The experiments

27 provide insights into how volatiles contribute to crystal mush rejuvenation (i.e.,
28 increase of melt fraction). However, H₂O diffusion alone is not sufficient to promote
29 melt extraction from short- and long-lived mushes in the Earth's crust.

30

31 **Introduction**

32 The link between crustal architecture, the fluxes of magma through the crust,
33 and the attendant transfer of heat, mass, and fluid, is fundamental to our
34 understanding of crust-forming processes (e.g., [Hildreth and Moorbath 1988](#); [Huppert](#)
35 [and Sparks 1988](#); [Barboza and Bergantz 1997](#); [Tatsumi, 2000](#); [Bohrson and Spera](#)
36 [2001](#); [Solano et al. 2012](#); [Dungan and Davidson, 2004](#); [Dufek and Bergantz 2005](#);
37 [Annen et al. 2006](#); [Takahashi et al. 2007](#); [Huber et al. 2009](#); 2010; [Chiaradia et al.](#)
38 [2011](#); [Paterson et al. 2011](#); [Paterson and Ducea 2015](#)). In arc settings in which large
39 volatile budgets are released from the subducting slab (e.g., [Ulmer and Trommsdorff](#)
40 [1995](#); [Poli and Schmidt 1995](#); [Schmidt and Poli 1998](#)), the Earth's continental crust is
41 a processing zone, fed by mantle-derived, hydrous magmas (H₂O contents of 1-7
42 wt%, with 4 wt% on average; [Ulmer 2001](#); [Plank et al. 2013](#); CO₂ contents of > 250
43 ppm; [Cervantes and Wallace 2003](#); [Blundy et al. 2010](#)) and releasing H₂O-rich,
44 differentiated (felsic) melts to shallower crustal depths where they degas and
45 crystallise. The resultant felsic crystal mushes (i.e., partially molten rocks between the
46 liquidus and solidus temperatures) are often rheologically stalled bodies with average
47 solid fractions (ϕ) of 0.4-0.6, close to the microstructural transition from a suspension
48 of isolated crystals in a melt to a solid framework containing a through-going network
49 of melt channels (e.g., [Lejeune and Richet 1995](#); [Caricchi et al. 2007](#)). Felsic crystal
50 mushes may be thermally stable for long periods of time ([Glazner et al. 2004](#);
51 [Caricchi and Blundy 2015](#)); whether they are mobilised to erupt, or solidify to form

52 plutons, is primarily a function of the extent to which they are sustained by further
53 additions of heat and volatiles. An important process of heat and volatile addition is
54 the injection of hydrous mafic magmas into crystal mushes. Many volcanic rocks
55 carry evidence of mafic injection shortly before eruption, and this process has been
56 invoked as an eruption trigger (e.g., [Eichelberger and Izbekov 2000](#); [Murphy et al.](#)
57 [2000](#); [Suzuki and Nakada 2007](#); [Sigmundsson et al. 2010](#); [Tomiya et al. 2013](#)).

58 Mafic-felsic magma interactions have the potential to remobilise near-solidus
59 felsic crystal mushes by means of heat ([Burgisser and Bergantz 2011](#); [Tapster et al.](#)
60 [2016](#)) or volatiles ([Bachmann and Bergantz 2006](#); [Parmigiani et al. 2016](#)), or a
61 combination of both ([Huber et al. 2011](#); [Parmigiani et al. 2014](#)). Felsic crystal mush
62 "defrosting" ([Huber et al. 2010](#)) could be triggered by the percolating buoyant
63 volatiles with a high specific heat, which can assist the reactivation of the mush by
64 allowing significant heat advection. Volatiles are also essential in the rheological
65 rejuvenation of crystal mushes by lowering their viscosity (e.g., [McByrne and Murase](#)
66 [1984](#); [Petford 2003](#); [Ardia et al. 2008](#); [Pistone et al. 2013](#)), density (e.g., [Ochs and](#)
67 [Lange 1999](#); [Bachmann and Bergantz 2004](#); [Malfait et al. 2014](#); [Ardia et al. 2014](#)),
68 and liquidus temperature (e.g., [Tuttle and Bowen 1958](#); [Johannes and Holtz 1996](#);
69 [Pistone et al. 2016](#)), reducing the crystal content by partial melting ([Huber et al.](#)
70 [2010](#)). Rejuvenation of the mush can be enhanced by high volatile content (> 4 wt%
71 H_2O) in the mafic intrusion and low confining pressure (< 2 kbar; volatile-saturated
72 conditions). However, at lower initial volatile contents (< 4 wt% H_2O) and higher
73 pressure (3-4 kbar; volatile-undersaturated conditions) volatiles may stall at the
74 interface between the two magmas because they do not achieve the residual saturation
75 threshold (i.e., lack of gas permeability). Under these conditions volatiles prevent
76 defrosting of the mush and cooling of the mafic body as heat transfer is impeded (i.e.,

77 "thermos bottle effect"; Carrigan 1988; Koyaguchi and Kaneko 1999; 2000; Huber et
78 al. 2009; 2010). When heat advection by volatile flux following multiple mafic pulses
79 intruding into a felsic crystal mush is efficient, it may trigger mush rejuvenation
80 and/or melt extraction.

81 Insights into mafic-felsic magma interactions are provided by numerous field
82 examples (e.g., Poldervaart and Taubeneck 1959; Loomis 1963; Moore and
83 Lockwood 1973; Shannon et al. 1982; D'Lemos 1987; Frost and Mahood 1987;
84 Gourgaud and Villemant 1992; Seaman and Ramsey 1992; Sisson et al. 1996;
85 Humphreys et al. 2010). A well-known example is the Tertiary Adamello Massif
86 (Italy), a batholith characterised by tonalite and subordinate granodiorite plutons
87 associated with small mafic/ultramafic intrusions, syn-plutonic mafic dykes and sills,
88 and ubiquitous mafic inclusions (Blundy and Sparks 1992; John and Blundy 1993;
89 Broderick et al. 2015; Hürlimann et al. 2016). Mixing textures between tonalite and
90 mafic magmas are apparent in the field. The mafic bodies are texturally and
91 compositionally heterogeneous as a result of variable assimilation of tonalite leading
92 to xenocrystic textures. For example, reaction of quartz phenocrysts from the tonalite
93 with fine-grained, dark, hornblende-bearing mafic magma produces coronas of green
94 hornblende (Figure 1). The presence of hornblende in the gabbroic rock suggests
95 significant H₂O in the hot (1050 °C) mafic melt (≥ 4 wt% H₂O; e.g. Yoder and Tilley
96 1962; Holloway and Burnham 1972), which ascended rapidly from the deep crust (7
97 kbar; Ulmer 1988; 2007; Ulmer et al. 1983) and interacted with hot (850 °C), partially
98 molten tonalite (Figure 1). Disaggregation and swarms of mafic inclusions, schlieren
99 and sub-parallel sheets of fine-grained mafic material, intimately mingled with the
100 crystal-rich tonalite. In the light of such observations, the tonalite body evidently was
101 in a mushy state, and could be mobilised with sufficient ease to allow partial

102 hybridisation ([Blundy and Sparks 1992](#)). Mobilisation was made possible by the
103 transfer of heat to the tonalite from the cooling mafic magma. Diffusion and/or
104 exsolution of volatiles from the mafic sheets, as evinced by the ubiquitous gabbroic
105 pegmatites, would have facilitated host rock mobilisation. Throughout the Adamello
106 batholith, but most notably in the southern part, hydrous mafic magmas intrude felsic
107 host magmas, supplying heat and volatiles that can be seen to contribute to the
108 physical destabilisation and extraction of melts from the host ([Ulmer et al. 1983](#);
109 [Blundy and Sparks 1992](#)). Particularly, field observations of the leucogranite dikes
110 extending radially out from the Listino Ring Complex are suggestive of residual melt
111 that was expelled from Monoccola Granodiorite after the emplacement of the hydrous
112 Listino Ring Gabbro ([John and Blundy 1993](#)). The rapid cooling and crystallisation of
113 this gabbro led to volatile exsolution and consequent volume expansion of the
114 overlying mush, resulting in roof uplift and the formation of inward dipping shear
115 fractures on the shoulders of the melt-mush system. At the same time, the release of
116 heat and volatiles caused partial melting and remobilisation of the Monoccola
117 Granodiorite mush and consequent melt extraction as confirmed by the leucogranite
118 dikes of the Listino Ring Complex, with an extracted melt volume of ~10-22 vol%, in
119 agreement with field observations ([Verberne et al. 2011](#)).

120 To simulate the chemical and physical conditions of crystal mush rejuvenation
121 and test melt extraction induced by hot, H₂O-rich mafic intrusions, we conducted
122 experiments on a suite of H₂O-undersaturated (4 wt% H₂O in the interstitial melt)
123 quartz-bearing dacite crystal mushes (crystal fraction, $\phi = 0.5-0.8$) subject to volatile
124 supply from an H₂O-saturated (≥ 6 wt% H₂O), crystal-free andesite at 4 kbar and 950
125 °C, in a closed-system (i.e., no net loss of volatiles). We applied an experimental
126 setup already used in previous works ([Yoder 1973](#); [Johnston and Wyllie 1988](#); [van der](#)

127 [Laan and Wyllie 1993](#)), but imposing an initial water gradient between andesite and
 128 dacite ([Pistone et al. 2016](#)). The isothermal nature of the experiments simulates the
 129 situation where intruding mafic magma (at ~1050 °C) and host tonalite (at ~850 °C)
 130 have equilibrated thermally at the interface (i.e., the temperature within the
 131 experimental system is spatially and temporally uniform) following heat diffusion and
 132 prior to chemical interaction. This situation is consistent with the more rapid diffusion
 133 of heat compared to most chemical components, including H₂O (i.e. thermal
 134 diffusivities are of the order of 10⁻⁷ m²/s in H₂O-bearing rhyolitic melts at > 800 °C;
 135 [Romine et al. 2012](#); the diffusivity of H₂O is about 10⁻¹⁰ m²/s in hydrous rhyolite at
 136 950 °C and 4 kbar [experimental conditions of this study]; [Ni and Zhang 2008](#)). The
 137 two systems are characterised by different liquidus temperatures (816 °C in the
 138 andesite and 923 to 1109 °C in the dacite, depending on the crystal content; [Pistone et](#)
 139 [al. 2016](#)), which are mainly dictated by the initial H₂O contents in each end-member.
 140 The subsequent change of liquidi in both systems, with the andesite liquidus rising
 141 and the dacite liquidus decreasing, is caused by the H₂O diffusion from the andesite to
 142 the dacite during experiments ([Pistone et al. 2016](#)). At the conditions of the
 143 experiment the H₂O content of the felsic crystal mush is limited by the H₂O stored in
 144 the interstitial melt phase, thus the *bulk* mush is always H₂O-undersaturated. Once it is
 145 heated the melting phase relations, in the absence of added H₂O, will be characterised
 146 by water activity (*a*H₂O) less than one. This limits the amount of melt production that
 147 can occur by heating alone. This situation prevails even when the interstitial melt
 148 phase is H₂O-saturated. The H₂O-undersaturated nature of the bulk felsic crystal mush
 149 therefore simulates the condition of a mush that experienced thermally-induced,
 150 dehydration partial melting rendering the melt undersaturated by the time that
 151 diffusive addition of H₂O starts to play a role. Then, the crystallinity of the felsic

152 mush reflects different degrees of melting of the original mush after the release of the
153 heat by the intruding mafic magma. The mafic end-member is initially crystal-free
154 consistent with rapid ascent to shallow depth without crystallising en route. The
155 equilibration pressure is ~ 4 kbar (minimum pressure in a conventional piston
156 cylinder), comparable to that in the Adamello Massif (2-3 kbar). The run products
157 reported here are those presented by [Pistone et al. \(2016\)](#), who mainly focussed on the
158 kinetics of nucleation and crystallisation and consequent formation of unidirectional
159 solidification textures or comb layering in mafic enclaves. Here we concentrate on
160 selected run products to show the H₂O diffusion from crystallising mafic magmas and
161 how this enhances further partial melting of the felsic mushes, physical changes in the
162 residual melt phase (i.e., density and viscosity) and, potentially, melt extraction after
163 heat and H₂O diffusion.

164

165 **Experimental methodology**

166 Sample preparation and synthesis procedures are described in detail in [Pistone](#)
167 [et al. \(2016\)](#). Cylindrical samples (3 mm diameter and length ranging from 1.2 to 3.6
168 mm) of synthetic hydrous dacite crystal mush, with different fractions of quartz
169 particles (F50: $\phi = 0.5$; F60: $\phi = 0.6$; F70: $\phi = 0.7$; F80: $\phi = 0.8$; H₂O ranging from
170 2.1 wt.% in the least crystalline sample to 0.84 wt.% at the highest crystallinity), were
171 juxtaposed with hydrous (≥ 6 wt% H₂O) crystal-free andesite glass. To ensure a
172 perfect initial contact between the interacting samples, the synthesised glasses were
173 polished on the top and bottom surfaces, and inserted in welded Au capsules (3-4 mm
174 diameter), which, in turn, were inserted in larger Mo-lined Au capsules (6 mm
175 diameter) filled with Al₂O₃ powder and deionised H₂O (0.1-0.2 ml). Two different
176 interaction setups were used: i) classic two-layer Setup A with felsic overlying mafic,

and ii) "intrusion-type" Setup B with mafic sandwiched between felsic samples. The two approaches allowed simulation of mafic-felsic magma interaction at different mass ratios (mafic-felsic ratio of ~1:1 in Setup A, and ~1:2 in Setup B). Experiments were carried out in an end-loaded [Boyd and England \(1960\)](#)-type piston cylinder apparatus using a 19 mm talc-pyrex, tapered-furnace cell ([McDade et al 2002](#)). Calibrations (based on water solubility in silicic melts) suggest a 20% lower value than the 5 kbar calculated from the hydraulic oil pressure on the piston. As a result our sample pressure is believed to be in the range 4 to 4.5 kbar. Temperature was monitored by a D-type ($W_{97}Re_3/W_{75}Re_{25}$) thermocouple connected to a Eurotherm 800 series controller, with no correction for the pressure effect on the emf ([Mao and Bell 1971](#)). The hot piston-out technique ([Johannes et al. 1971](#)) was used in all experiments. The intrinsic fO_2 of this assembly is relatively oxidised (NNO+1 to +2). As a result of the reduced conditions used for preparation of the starting material (~NNO-4), the oxidising external environment might encourage H_2 to diffuse out of the sample capsule with a simultaneous conversion of Fe^{2+} to Fe^{3+} . However, our use of Au inner and Mo-lined outer Au capsules was designed to minimise H_2 loss; there was no obvious loss of H_2O at the sample edge and certainly not in the centre of the experiment where we report our data. Experiments ran for 24 hours and were terminated by turning off the power. Recovered charges were impregnated in epoxy and polished prior to analytical inspections.

Analytical techniques

EPMA, FEG-EPMA, and SEM

Glass and mineral compositions from the starting materials and experimental charges were analysed with a conventional, tungsten-sourced 5-WD spectrometer

202 CAMECA SX-100 wavelength-dispersive electron probe micro-analyser (EPMA).
203 Glass compositions were investigated with a 15 kV accelerating voltage, 2-5 nA beam
204 current and 10-20 μm diameter (defocused) beam, and a counting time of 20 s (peak)
205 and 10 s (background). Minerals were analysed with a focused (1 μm) 10 nA beam
206 current and 20 kV accelerating voltage. Natural and synthetic standards were
207 employed and data were ZAF corrected. Peak count times of 60 s for Ca, Al, Ti, Fe
208 and Mg, 30 s for Si, K, and 20 s for Na. Spectrometers were set to analyse K, Na and
209 Si first. Primary calibrations used a mixture of synthetic and natural standards and
210 secondary standards of Kakanui kaersutite KK1 ([Jarosewich et al. 1980](#)), natural
211 diopside, USGS basaltic glass reference BCR2-G ([Govindaraju 1994](#)) and hydrous
212 dacite glass F0 ([Pistone et al. 2016](#)). Glass and mineral compositions are reported by
213 [Pistone et al. \(2016\)](#).

214 Using the approach of [Saunders et al. \(2014\)](#) to analyse crystal zoning, lines of
215 high-spatial resolution spot analyses through quartz crystals and surrounding glass in
216 representative run product F70-M were conducted using a JEOL 8530F field emission
217 gun electron probe micro-analyser (FEG-EPMA). Analyses were carried out with a 10
218 kV acceleration voltage, 1 nA beam current, and 1 μm beam diameter. Primary
219 calibrations for FEG-EPMA used the same primary and secondary standards as
220 conventional EPMA. FEG-EPMA data are reported in Supplementary Materials.

221 Backscattered (BSE) images of run products were acquired with a Hitachi S-
222 3500N quad solid-state BS detector scanning electron microscope (SEM). An
223 accelerating voltage of 15 to 25 kV and a beam current of 1 nA were employed to
224 obtain good contrast between glass and minerals. Images were used to estimate
225 volume fraction and size of the different phases in different portions of the run
226 products using JMicro-Vision v1.2.7.

SIMS

Glassed starting materials and run products were analysed by secondary ion mass spectrometry (SIMS) for dissolved H₂O using a CAMECA ims-4f ion microprobe at the EIMF of the University of Edinburgh. Au-coated samples were analysed with a 1.5 nA, 10.8 kV ¹⁶O⁻ beam focussed to a 10 μm spot, with ~15 keV net impact energy. Positive secondary ions were extracted at 4.5 keV with a 75±40 eV offset to minimise molecular ion transmission. Prior to each analysis, a 7 μm² raster was applied for 2 minutes at the target glass areas to remove any surface contamination around the edge of the sputter pit. NIST-610 (Hinton 1999) and natural and synthetic hydrous silica-rich glasses (including the crystal-free felsic and mafic compositions) were used as standards to monitor the H/Si ion yield and background at the start of each day. The number of counted cycles was 10, corresponding to a counting time of about 10 minutes. In addition to ¹H and ³⁰Si, ⁷Li, ¹¹B, ²⁶Mg, ⁴²Ca, ⁴⁷Ti, and ⁵⁴Fe were measured, with the heavier elements used to assess consistency with major element compositions from EPMA. The background H₂O correction measured on NIST-610 was equivalent to ≤ 0.2 wt% H₂O. The analytical data, Si-normalised and corrected using the NIST-610 standard of the GeoReM database (<http://georem.mpch-mainz.gwdg.de/>), are reported in Pistone et al. (2016).

Raman spectroscopy

Raman-based spectra and OH-intensity maps of the run products were performed using a Thermo Scientific™ DXR™ confocal Micro-Raman spectrometer (grating of 1800 mm⁻¹) equipped with an Olympus microscope and an Ar-ion laser (wavelength of 514.5 nm). Reflected light optics was used to select analysis locations.

Raman spectra for H₂O determination were acquired for 120 s in the range of 200-1500 and 2800-3850 cm⁻¹ encompassing low- and high-frequency vibrational bands associated with the silicate glass network and vibration modes of OH and H₂O, respectively, at room conditions (25 °C and 1 bar). The Raman optics and precision-control stage give lateral and vertical resolution of 250 nm and 500 nm, respectively, and were used in rapid spectra acquisition mode (less than 100 ms for a single spectrum). The effective volume resolution was better than 5 µm³. Maps were obtained in confocal mode and spectra (120 s each) were obtained from a grid of points spaced 2 µm apart, at a constant sample depth of 5±2 µm. Although the objective was to map gradients, some quantification of H₂O contents was attempted using the Raman spectra and a set of well-characterised hydrous rhyolite and andesite glass standards with known H₂O contents determined by SIMS at the University of Edinburgh and Karl-Fischer titration at ETH-Zürich (Pistone et al. 2015). The calibration followed the method of Le Losq et al. (2012) relating the peak ratios of the low-frequency peak (at 1128 ±5 cm⁻¹) to the OH/H₂O peak (at 3568 ±10 cm⁻¹).

Results

Run products are labelled with the abbreviations of the two or three separate components loaded and labelled in the following way; e.g., M-F50 is a couple made of mafic andesite (M), which is always crystal-free, and felsic dacite (F) that has a specified initial crystal fraction (ϕ) of 0.5 (F50); e.g. F60-M-F60 is a sandwich of andesite between two layers of crystal-bearing (ϕ = 0.6) dacite, etc.

Microstructures

All run products are characterised by extensive crystallisation of the andesite sample, which becomes more evident when Setup B (F-M-F sandwich) is used (Figure 2B). The andesite shows a decrease of the local glass fraction by ~ 0.7 to ~ 0.95 towards the interface. Conversely, the dacite crystal mushes are characterised by the presence of a thin (30 to 60 μm thick) portion of crystal-free glass (with rare vesicles) close to the interface with the andesite sample (see image inset in Figure 2A). Moving further from the interface, this layer is followed by another relatively thin (~ 150 - 200 μm) region of nuclei and microlites of hornblende (accompanied by a few isolated vesicles), which are mostly located close to the quartz crystal clusters (see image inset in Figure 2A). Quartz crystals, which make up the solid framework of the felsic mushes, display smooth boundaries (Figure 2D) and, in some places, are surrounded by 1-3 μm -sized hornblende microlites (see image inset in Figure 2A). More importantly, it is possible to observe that the dacite mushes with $\phi < 0.8$ are affected by large textural heterogeneities at several hundreds μm - to mm-scale, characterised by large crystal-free glass pools, whose areas decrease with increasing crystallinity (Figure 2A-C). At $\phi = 0.8$, there is lack of glass-enriched portions generated during interaction experiments (see [Pistone et al. 2016](#)).

Chemistry

One of the major chemical changes observed in the glass of the felsic mushes following interaction is an increase in SiO_2 content above that of the starting glass. This is particularly evident where the glass is surrounded by quartz crystals, suggestive of quartz dissolution, as confirmed by FEG-EPMA analysis (Figure 2D). More details on chemical mixing in the run products are reported in the study of [Pistone et al. \(2016\)](#). Here we focus attention on the variation of H_2O .

At the end of the run H₂O contents in the glass (Figure 2) increase from the dacite (5-6 wt% H₂O) to the andesite (7-8 wt%), consistent with a flux of H₂O from the latter to the former. In the dacite H₂O contents are high in proximity to the interface, particularly in the glass-rich regions, but relatively close to the initial H₂O content in glass pockets within or surrounded by quartz crystal clusters and in the glassy portions more than 0.2 mm from the interface (Figure 2A-C). Bulk H₂O contents change dramatically from the andesite to the dacite, particularly along the interface (< 1 mm distance from the interface; Figure 3) where the andesite is largely crystalline ($\phi > 0.9$), but the dacite is glassy or displays limited hornblende crystallisation ($\phi < 0.07$) around quartz crystals (see image inset in Figure 2A). Bulk H₂O contents (i.e. accounting for the presence of crystals) vary from < 0.8 wt% in the upper portion of the andesite (< 1 mm from the interface) to 1-3 wt% in the dacite. We observe that, overall, the greater the crystal content in the dacite mush, the higher the H₂O content in the glass and the lower the H₂O content in the bulk dacite (Figure 3) suggestive of local H₂O solubility increase as the residual melt becomes enriched in SiO₂ through quartz dissolution (Figure 2D). The run product F80-M-F80 (Figure 3D) represents an exception since both H₂O contents in the glass (3-4 wt%) and in the bulk dacite (0.4-0.6 wt%) are lower than H₂O contents in the other run products (Figure 3), suggestive of a combination of large crystal content in the mush and dissolution of quartz in the residual melt. These results demonstrate how the interplay between crystallisation (reducing bulk H₂O storage capacity) and melting (increasing storage capacity) mediates the flux of H₂O from the andesite to the dacite. The implications of these coupled processes for natural mixed-magma settings are discussed below.

Discussion

326 Melt dehydration during isothermal decompression is a widespread cause of
327 crystallisation in hydrous magmas due to the strong effect of H₂O on liquidus
328 temperatures and phase relations (Yoder et al. 1957; Tuttle and Bowen 1958;
329 Burnham and Jahns 1962; Merrill and Wyllie 1975; Blundy and Cashman 2001).
330 Thus, we expect that volatile exsolution, outgassing, and diffusion, including changes
331 in H₂O pressure, that occur during interactions between hydrous magmas in the crust
332 might also have significant consequences for phase relations, notably by maintaining
333 high $a_{\text{H}_2\text{O}}$ in the felsic mush.

334 The experiments show that isothermal interaction of mafic and felsic magmas
335 produces complex relationships. The interaction (or contact) temperature (controlled
336 by heat transfer) and liquidus temperature (controlled by volatile transfer) of each
337 domain determines: i) undercooling-driven crystallisation when contact temperature <
338 liquidus temperature, or ii) superheating-driven melting when contact temperature >
339 liquidus temperature. In the case of isothermal interaction, changes in liquidus
340 temperature are driven by the movement of water from one magma to the other.
341 Undercooling driven by water loss is termed "chemical undercooling" by Pistone et al.
342 (2016). The textures that result from undercooling depend on its magnitude: large
343 values of undercooling favour crystal nucleation, while small values of undercooling
344 favour crystal growth (e.g., Brandeis and Jaupart 1987; Cashman and Blundy 2000;
345 Hort 1998). For chemical undercooling, it is the rate of loss of H₂O that determines
346 the texture. A front of increasing liquidus temperature, due to H₂O loss and
347 consequent crystallisation, will propagate into the mafic domain (i.e., inward
348 solidification front driven by volatile release; Podlachikov and Wickham, 1994), as
349 H₂O moves to the felsic domain (Figures 2-3). Depending on the evolution of
350 undercooling with time the migration of the crystallisation front may be dominated

351 either by nucleation or growth ([Pistone et al. 2016](#)). In natural hydrous magmas the
352 chemical (H₂O-driven) and thermal (temperature-driven) "undercooling fronts"
353 propagate away from the interface at rates controlled by the relative diffusivities of
354 H₂O and heat. Although heat diffuses three orders of magnitude faster than H₂O, the
355 effect of reducing the temperature on undercooling is much less pronounced than the
356 effect of dehydration on raising the liquidus temperature in the mafic magma. The
357 corollary occurs in the felsic domain, where both heat and H₂O are being supplied,
358 leading to "chemical superheating" as the liquidus temperature is reduced by H₂O
359 addition. The addition of H₂O maintains $a_{\text{H}_2\text{O}}$ at or close to one in the mush, thereby
360 enabling higher degrees of melting than would be possible if bulk mush H₂O content
361 was limited by that originally contained in the residual melt phase.

362 In the light of field observations and rock textures explored in the natural
363 samples from the Val Fredda Complex in the Tertiary Adamello Batholith (Alps,
364 Italy) (Figure 1), and the petrological constraints reported in previous works ([Blundy](#)
365 [and Sparks 1992](#); [John and Blundy 1993](#); [Ulmer 1988](#); [2007](#); [Ulmer et al. 1983](#);
366 [Broderick et al. 2015](#); [Hürlimann et al. 2016](#)), here we attempt to evaluate the
367 independent effects of heat and H₂O addition to a felsic system destabilised by a
368 mafic intrusion. We underline that the design of our experiments did not capture the
369 effect of heat diffusion during magma mixing. In a natural scenario the fast transfer of
370 heat from the intruding water-rich mafic to the water-saturated felsic magma (i.e.
371 crystals plus H₂O-bearing interstitial melt) dictates a temperature convergence for
372 both systems, due to which the mafic magma cools and initiates to crystallise as a
373 consequence of heat loss, whereas the felsic host is reheated and experiences partial
374 melting (Figure 4A). The felsic partial melting can affect a number of minerals such
375 as quartz, feldspar, biotite, amphibole; particularly, the melting of anhydrous phases,

such as the quartz particles used in our experiments, induces the felsic system to become water-undersaturated (Figure 4A). This condition drives a flux of H₂O from the cooling volatile-rich mafic intrusion. Therefore, the melting of anhydrous phases triggers more melting by "absorbing" water under isothermal conditions. The addition of water suppresses the felsic liquidus temperature (Figure 4B), down to as much as 800 °C (Pistone et al. 2016). Concomitantly, the mafic magma dehydrates and is fated to quench chemically against the felsic system, leading eventually to complete solidification and "viscous death" (Annen et al. 2006; Pistone et al. 2013). In such a context, the overall felsic mush rejuvenation process consists of two main stages: i) an "early rejuvenation stage" in which the partial melting of the felsic host is heat-driven (Figure 4A); and ii) a "mature rejuvenation stage" in which the partial melting of the felsic system is water-driven (Figure 4B). In detail, the final equilibration temperature depends on the heat contents of the mafic and felsic systems at the scale on which interaction occurs. In nature, masses and volumes of igneous bodies are extremely difficult to estimate in the field since erosion and tectonic processes tend to obscure such information. In the case of Adamello, the intruding mafic magmas consist of dykes and swarms of inclusions that make it even more difficult assess the effective mass and volume of the intruding mafic magmas.

Implications

Petrological and numerical studies have proposed that rejuvenation might generate active magma chambers in the Earth's crust (e.g., Bachmann and Bergantz 2003; Bain et al. 2013). Silicic magma bodies composed of a touching framework of crystals and interstitial melt, close to their rheological lockup point, are remobilised in response to the injection of hotter, hydrous mafic magma providing mass, heat and

401 volatiles (Eichelberger 1995; Bachmann and Bergantz 2003; Huber et al. 2009;
 402 Parmigiani et al. 2014). As shown in Figure 4, heat and volatile transfer from a
 403 crystallising layer of injected mafic magma, ponded at the floor of a silicic pluton or
 404 magma body, can melt, weaken, and destroy the crystalline framework of the
 405 underlying silicic mush, rendering it gravitational unstable (e.g., Jellinek and Kerr
 406 1999; Bain et al. 2013). When the crystalline framework is not fully destroyed, and,
 407 thus, the felsic crystal mush remains partially molten, the rejuvenation process might
 408 not favour the mobilisation of the whole mush, but can drive the extraction of
 409 interstitial melts from the mush, potentially generating caps or lenses of evolved,
 410 crystal-poor melts (e.g., Hildreth and Wilson 2007; Czappon et al. 2012). In the light
 411 of our experiments simulating the water-driven "mature rejuvenation stage" of felsic
 412 systems (Figure 4B), we propose to test whether water diffusion promotes not only
 413 enhanced melt production, but also melt extraction from the mush. Specifically, we
 414 quantify the decrease in density (ρ_{melt}) and viscosity (η_{melt}) of silicic melt affected by
 415 the flux of H₂O via diffusion, and understand how these physical changes assist melt
 416 extraction from the mush. Figures 5 and 6 show ρ_{melt} and η_{melt} profiles of the residual
 417 melt in both dacite and andesite. ρ_{melt} and η_{melt} were calculated using the models of
 418 Lange and Carmichael (1987) and Giordano et al. (2008), respectively, under our
 419 experimental conditions of temperature and pressure, and using the analytical data
 420 from Pistone et al. (2016). The density model of Lange and Carmichael (1987) was
 421 combined with the densification model of Ardia et al. (2014), who propose a linear
 422 increase of ρ_{melt} at $P < 15$ kbar. The 1 bar-based viscosity model of Giordano et al.
 423 (2008) was modified using a correction factor of 1.8 log units in η_{melt} to include the
 424 pressure effect on the viscosity of polymerised melts, with η_{melt} decreasing with
 425 pressure under the conditions of > 800 °C and < 15 kbar (Ardia et al. 2008; 2014;

426 [Pistone et al. 2012](#)). In our interaction experiments ρ_{melt} values are higher in the
 427 andesite (2250-2450 kg/m³; Figure 5) than in the dacite (2050-2150 kg/m³; Figure 5).
 428 In some dacite portions where quartz crystals isolate melt pockets, the inferred ρ_{melt} is
 429 slightly higher (2200-2250 kg/m³). η_{melt} tends to increase by 1 log unit from andesite
 430 to dacite (Figure 6). Only in run product F80-M-F80 η_{melt} of andesite is higher than
 431 that of dacite (Figure 6). The increase of both ρ_{melt} and η_{melt} in the andesite and their
 432 decrease in the dacite are consistent with andesite dehydration and dacite hydration
 433 respectively.

434 The simultaneous decrease of ρ_{melt} and η_{melt} in the felsic melts may lead to the
 435 extraction of the residual silicic melt from the mush. In nature, in the absence of other
 436 processes such as gas-driven filter pressing ([Anderson et al. 1984](#); [Sisson and Bacon](#)
 437 [1999](#); [Pistone et al. 2015](#)), to be effective, melt extraction must occur within the
 438 lifetime of crystal mushes in the Earth's crust (average 10⁴-10⁵ years; [Bachmann and](#)
 439 [Bergantz 2004](#), and references therein; 10⁷ years for assembled plutons; [Glazner et al.](#)
 440 [2004](#)). Using a simple approximation of the H₂O diffusion length scale ($x=t \times DH_2O$,
 441 [Watson 1982](#); [Baker 1991](#); with $DH_2O = 3 \cdot 10^{-10}$ m²/s from [Ni and Zhang 2008](#), and t
 442 = experimental duration), in our experiments H₂O penetrates the whole felsic sample
 443 ($x = 5.4$ mm) within 24 hours and drives lower ρ_{melt} and η_{melt} as well as ρ_{bulk} and η_{bulk}
 444 (Figures 5-6). However, in natural systems at the scale of tens of meters to kilometre
 445 scale, H₂O diffusion is not sufficient to stimulate melt extraction within the lifetime of
 446 felsic plutons in the Earth's crust, including those of high longevity such as the
 447 Tuolumne Intrusive Suite, Yosemite Valley (~10 My; [Glazner et al. 2004](#); Figure 7).

448 In conclusion, we investigated experimentally H₂O transfer during high-
 449 temperature and -pressure mixing between H₂O-undersaturated dacite crystal mush

450 and H₂O-saturated andesite magma at crustal conditions (950 °C, 4 kbar) under
451 conditions that heat transfer had already occurred. The microstructural and chemical
452 results for the run products show that isothermal undercooling results from a change
453 in liquidus temperatures of the interacting magmas with changing H₂O content. Mafic
454 samples crystallised at the same time as H₂O diffusion into the felsic end-members,
455 which became enriched in H₂O, generating partial melting of the crystal network (i.e.,
456 quartz dissolution) and inducing changes in the physical properties (i.e., density and
457 viscosity) of the residual melt. Mixing between pulses of hot and H₂O-saturated mafic
458 magma and near-solidus felsic crystal mushes in the Earth's crust are important
459 instances of heat and volatile transfer to the felsic system that may promote crystal
460 mush rejuvenation (through progressive reheating and partial melting). The heat-
461 driven rejuvenation stage first and, then, the water-driven melting of the felsic mush
462 may lead to a consequent extraction of the residual melt from the mush. In the latter
463 stage of the rejuvenation process, large addition of water into felsic magmas, which
464 became H₂O-undersaturated during partial melting of anhydrous phases due to heat
465 transfer, may reactivate "old" magma chambers (e.g., [Dolfi and Trigila 1978](#)) or
466 generate new ones (i.e., formation of "ghost" magma chambers; [Trigila et al. 2008](#)) by
467 decreasing liquidus temperature. This process of rejuvenation differs significantly
468 from that driven solely by the transfer of heat, because of the enhanced melt
469 productivity in the mush due to H₂O addition. However, using existing models for
470 testing melt extraction from mushes in a scenario similar to that experimentally tested,
471 water diffusion alone is not sufficient to drive melt extraction from a mush within the
472 lifetime of crustal felsic plutons. As reported in previous studies modelling melt
473 extraction from felsic mushes after being intruded by mafic intrusions (e.g.,
474 [Bachmann and Bergantz 2004; 2006; Huber et al. 2009; 2010; 2011; Parmigiani et al.](#)

2014), exsolved volatiles (i.e., gas bubbles) might play an essential role in favouring rapid melt extraction from felsic plutons. To our knowledge, there are no experimental constraints that can support the numerical results of the existing models; future investigations could assess how the mechanics and mechanisms of exsolved volatile transfer during magma mixing events might favour efficient melt extraction from felsic mushes.

Acknowledgments

SNSF Grant EPM-PBEZP2_14922 (to MP), and ERC Advanced Grant CRITMAG, NERC SIMS award IMF534/0514 and a Wolfson Research Merit Award (to JB) supported this research. We acknowledge the following for their help: S. Kearns and B. Buse for EPMA, FEG-EPMA, and SEM analyses (University of Bristol); R. Hinton for SIMS analyses (EIMF, University of Edinburgh); C. Clapham and D. Hawley for technical support (University of Bristol); J. Riker (University of Bristol) for providing hydrous glass standards for SIMS; Alberto Luisoni AG (Switzerland) and Nabaltec AG (Germany) for supplying quartz and APYRAL 60CD used in the starting materials; M. Petrelli, C. Huber, and an anonymous reviewer for their helpful comments on an earlier version of the manuscript.

References

- Anderson, A.T. Jr., Swihart, G.H., Artioli, G., and Geiger, C.A. (1984) Segregation vesicles, gas filter-pressing, and igneous differentiation. *Journal of Geology*, 92, 55-72.
- Annen, C., Blundy, J.D., and Sparks, R.S.J. (2006) The genesis of intermediate and silicic magmas in deep crustal hot zones. *Journal of Petrology*, 47, 505-539.

499 Ardia, P., Giordano, D., and Schmidt, M.W. (2008) A model for the viscosity of rhyolite as a function
500 of H₂O-content and pressure: a calibration based on centrifuge piston cylinder experiments.
501 *Geochimica et Cosmochimica Acta*, 72, 6013-6123.

502 Ardia, P., Di Muro, A., Giordano, D., Massare, D., Sanchez-Valle, C., and Schmidt, M.W. (2014)
503 Densification mechanisms of haplogranite glasses as a function of water content and pressure based
504 on density and Raman data. *Geochimica et Cosmochimica Acta*, 138, 158-180.

505 Bachmann, O., and Bergantz, G.W. (2003) Rejuvenation of the Fish Canyon magma body: a window
506 into the evolution of large-volume silicic magma systems. *Geology*, 31, 789-792.

507 Bachmann, O., and Bergantz, G.W. (2004) On the origin of crystal-poor rhyolites: extracted from
508 batholithic crystal mushes. *Journal of Petrology*, 45, 1565-1582.

509 Bachmann, O., and Bergantz, G.W. (2006) Gas percolation in upper-crustal silicic crystal mushes as a
510 mechanism for upward heat advection and rejuvenation of near-solidus magma bodies. *Journal of*
511 *Volcanology and Geothermal Research*, 149, 85-102.

512 Bain, A.A., Jellinek, A.M., and Wiebe, R.A. (2013) Quantitative field constraints on the dynamics of
513 silicic magma chamber rejuvenation and overturn. *Contributions to Mineralogy and Petrology*, 165,
514 1275-1294.

515 Baker, D.R. (1991) Interdiffusion of hydrous dacitic and rhyolitic melts and the efficacy of rhyolite
516 contamination of dacitic enclaves. *Contributions to Mineralogy and Petrology*, 106, 462-473.

517 Barboza, S.A., and Bergantz, G.W. (1997) Melt productivity and rheology: complementary influences
518 on the progress of melting. *Numerical Heat transfer, Part A: Applications*, 31, 475-492.

519 Blundy, J.D., and Sparks, R.S.J. (1992) Petrogenesis of mafic inclusions in granitoids of the Adamello
520 Massif, Italy. *Journal of Petrology*, 33, 1039-1104.

521 Blundy, J.D., and Cashman, K.V. (2001) Magma ascent and crystallization at Mount St. Helens, 1980-
522 1986. *Contributions to Mineralogy and Petrology*, 140, 631-650.

523 Blundy, J.D., Cashman, K.V., Rust, A., and Witham, F. (2010) A case for CO₂-rich arc magmas. *Earth*
524 *and Planetary Science Letters*, 290, 289-301.

525 Bohrsen, W.A., and Spera, F.J. (2001) Energy-constrained open system magmatic processes II:
526 Application of energy-constrained assimilation–fractional crystallization (EC-AFC) model to
527 magmatic systems. *Journal of Petrology*, 42, 1019-1041.

528 Boyd, F.R., and England J.L. (1960) Apparatus for phase equilibrium measurements at pressures of up

529 to 50 kbars and temperatures to 1750 °C. *Journal of Geophysical Research*, 65, 741-748.

530 Brandeis, G., and Jaupart, C. (1987) The kinetics of nucleation and crystal growth and scaling laws for
 531 magmatic crystallization. *Contributions to Mineralogy and Petrology*, 96, 24-34.

532 Broderick, C., Wotzlaw, J.F., Frick, D.A., Gerdes, A., Ulianov, A., Günther, D., and Schaltegger, U.
 533 (2015) Linking the thermal evolution and emplacement history of an upper-crustal pluton to its
 534 lower-crustal roots using zircon geochronology and geochemistry (southern Adamello batholith, N.
 535 Italy). *Contributions to Mineralogy and Petrology*, 170, 28-44.

536 Burgisser, A., and Bergantz, G.W. (2011) A rapid mechanism to remobilize and homogenize
 537 crystalline magma bodies. *Nature*, 471, 212-215.

538 Burnham, C.W., and Jahns, R.H. (1962) A method for determining the solubility of water in silicate
 539 melts. *American Journal of Science*, 260, 721-745.

540 Caricchi, L., Burlini, L., Ulmer, P., Gerya, T., Vassalli, M., and Papale, P. (2007) Non-Newtonian
 541 rheology of crystal-bearing magmas and implications for magma ascent dynamics. *Earth and
 542 Planetary Science Letters*, 264, 402-419.

543 Caricchi, L., and Blundy, J.D. (2015) The temporal evolution of chemical and physical properties of
 544 magmatic systems. In Caricchi, L., and Blundy, J.D. (eds) *Chemical, Physical and Temporal
 545 Evolution of Magmatic Systems*. Geological Society of London, Special Publication, 422,
 546 <http://doi.org/10.1144/SP422.11>.

547 Carrigan, C.R. (1988) Biot number and thermos bottle effect: implications for magma chamber
 548 convection. *Geology*, 16, 771-774.

549 Cashman, K.V., and Blundy, J.D. (2000) Degassing and crystallization of ascending andesite and
 550 dacite. *Philosophical Transactions of the Royal Society A*, 358, 1489-1513.

551 Cervantes, P., and Wallace, P. (2003) Role of H₂O in subduction-zone magmatism: new insights from
 552 melt inclusions in high-Mg basalts from central Mexico. *Geology*, 31, 235-238.

553 Chiaradia, M., Müntener, O., and Beate, B. (2011) Enriched basaltic andesites from mid-crustal
 554 fractional crystallization, recharge, and assimilation (Pilavo Volcano, Western Cordillera of
 555 Ecuador). *Journal of Petrology*, 52, 1107-1141.

556 Czappon, G., Lukacs, R., Harangi, S., Mason, P.R.D., and Ntafllos, T. (2012) Mixing of crystal mushes
 557 and melts in the genesis of the Bogacs ignimbrite suite, northern Hungary; an integrated
 558 geochemical investigation of mineral phases and glasses. *Lithos*, 148, 71-85.

559 D'Lemos, R.S. (1987) Relationships between the Cobo Granite and the Bordeaux Diorite Complex,
 560 Guernsey. PhD Dissertation, University of Bristol.

561 Dolfi, D., and Trigila, R. (1978) The role of water in the 1944 Vesuvius Eruption. Contributions to
 562 Mineralogy and Petrology, 67, 297-304.

563 Dufek, J., and Bergantz, G.W. (2005) Lower crustal magma genesis and preservation: A stochastic
 564 framework for the evaluation of basalt-crust interaction. Journal of Petrology, 46, 2167-2195.

565 Dungan, M.A., and Davidson, J. (2004) Partial assimilative recycling of the plutonic roots of arc
 566 volcanoes: an example from the Chilean Andes. Geology, 32, 773-776.

567 Eichelberger, J.C. (1995) Silicic Volcanism: ascent of viscous magmas from crustal reservoirs. Annual
 568 Reviews of Earth and Planetary Science, 23, 41-63.

569 Eichelberger, J.C., and Izbekov, P.E. (2000) Eruption of andesite triggered by dyke injection:
 570 contrasting cases at Karymsky Volcano, Kamchatka and Mt Katmai, Alaska. Philosophical
 571 Transactions of the Royal Society A, 358, doi:10.1098/rsta.2000.0599.

572 Frost, T.P., and Mahood, G.A. (1987) Field, chemical, and physical constraints on mafic-felsic magma
 573 interaction in the Lamarck Granodiorite, Sierra Nevada, California. Geological Society of American
 574 Bulletin, 99, 272-291.

575 Giordano, D., Russell, J.K., and Dingwell, D.B. (2008) Viscosity of magmatic liquids: a model, Earth
 576 and Planetary Science Letters, 271, 123-134.

577 Glazner, A.F., Bartley, J.M., Coleman, D.S., Gray, W., and Taylor, R.Z. (2004) Are plutons assembled
 578 over millions of years by amalgamation from small magma chambers?. Geological Society of
 579 America Today, 14, 4-11.

580 Govindaraju, K., (1994) 1994 compilation of working values and sample description for 383
 581 geostandards. Geostandards Newsletter, 18, 1-158.

582 Gourgaud, A., and Villemant, B. (1992) Evolution of magma mixing in an alkaline suite: the Grande
 583 Cascade sequence (Monts-Dore, French Massif Central). Geochemical modeling. Journal of
 584 Volcanology and Geothermal Research, 52, 255-275.

585 Hildreth, W., and Moorbath, S. (1988) Crustal contributions to arc magmatism in the Andes of Central
 586 Chile. Contributions to Mineralogy and Petrology, 98, 455-489.

587 Hildreth, W., and Wilson, J.N. (2007) Compositional Zoning of the Bishop Tuff. Journal of Petrology,
 588 48, 951-999.

589 Hinton, R.W. (1990) Ion microprobe trace-element analysis of silicates.measurement of multi-element
590 glasses. *Chemical Geology*, 83, 11-25.

591 Holloway, J.R., and Burnham, C.W. (1972) Melting relations of basalt with equilibrium water pressure
592 less than total pressure. *Journal of Petrology*, 13, 1-29.

593 Holland, T., and Powell, R. (2001) Calculations of phase relations involving haplogranitic melts using
594 an internally consistent thermodynamic dataset. *Journal of Petrology*, 42, 673-683.

595 Holtz, F., Behrens, H., Dingwell, D.B., and Johannes, W. (1995) Water solubility in haplogranitic melts:
596 compositional, pressure and temperature dependence. *American Mineralogist*, 80, 94-108.

597 Hort, M. (1998) Abrupt change in magma liquidus temperature because of volatile loss or magma
598 mixing: effects on nucleation, crystal growth and thermal history of the magma. *Journal of*
599 *Petrology*, 39, 1063-1076.

600 Huber, C., Bachmann, O., and Manga, M. (2009) Homogenization processes in silicic magma
601 chambers by stirring and latent heat buffering. *Earth and Planetary Science Letters*, 283, 38-47.

602 Huber, C., Bachmann, O., and Manga, M. (2010) Two competing effects of volatiles on heat transfer in
603 crystal-rich magmas: thermal insulation vs defrosting. *Journal of Petrology*, 51, 847-867.

604 Huber, C., Bachmann, O., and Dufek, J. (2011) Thermo-mechanical reactivation of locked crystal
605 mushes: melting-induced internal fracturing and assimilation processes in magmas. *Earth and*
606 *Planetary Science Letters*, 304, 443-454.

607 Humphreys, M.C.S., Edmonds, M., Christopher, T., and Hards, V. (2010) Magma hybridisation and
608 diffusive exchange recorded in heterogeneous glasses from Soufrière Hills Volcano, Montserrat.
609 *Geophysical Research Letters*, 37, L00E06.

610 Huppert, H.C., and Sparks, R.S.J. (1988) The fluid dynamics of crustal melting of injection of basaltic
611 sills. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, 79, 237-243.

612 Hürlimann, N., Müntener, O., Ulmer, P., Nandedkar, R., Chiaradia, M., and Ovtcharova, M. (2016)
613 Primary magmas in continental arcs and their differentiated products: petrology of a post-plutonic
614 dyke suite in the Tertiary Adamello Batholith (Alps). *Journal of Petrology*, 57, 495-534.

615 Jarosewich, E., Nelen, J.A., and Norberg, J.A. (1980) Reference samples for electron microprobe
616 analysis. *Geostandard Newsletter*, 4, 43-47.

617 Jellinek, A.M., and Kerr, R.C. (1999) Mixing and compositional stratification produced by natural
618 convection 2. Applications to the differentiation of basaltic and silicic magma chambers and

619 komatiite lava flows. *Journal of Geophysical Research*, 104, 7203-7218.

620 Johannes, W.J., Bell, P.M., Mao, H.K., Boettcher, A.L., Chipman, D.W., Hays, J.F., Newton, R.C., and
621 Seifert, F. (1971) An interlaboratory comparison of piston-cylinder pressure calibration using the
622 albite breakdown reaction. *Contributions to Mineralogy and Petrology*, 32, 24-38.

623 Johannes, W.J., and Holtz, F. (1996) *Petrogenesis and Experimental Petrology of Granitic Rocks*.
624 Berlin, Springer, 335 pp.

625 John, B.E., and Blundy, J.D. (1993) Emplacement-related deformation of granitoidmagmas, southern
626 Adamello Massif, Italy. *Geological Society of American Bulletin*, 105, 1517-1541.

627 Johnston, A.D., and Wyllie, P.J. (1988) Interaction of granitic and basic magmas: experimental
628 observations on contamination processes at 10 kbar with H₂O. *Contributions to Mineralogy and*
629 *Petrology*, 98, 352-362.

630 Koyaguchi, T., and Kaneko, K. (1999) A two-stage thermal evolution model of magmas in continental
631 crust. *Journal of Petrology*, 40, 241-254.

632 Koyaguchi, T., and Kaneko, K. (2000) Thermal evolution of silicic magma chambers after basalt
633 replenishment. *Transactions of the Royal Society of Edinburgh*, 91, 47-60.

634 Lange, R.A., and Carmichael, I.S.E. (1987) Densities of Na₂O-K₂O-CaO-MgO-FeO-Fe₂O₃-Al₂O₃-
635 TiO₂-SiO₂ liquids: new measurements and derived partial molar properties. *Geochimica et*
636 *Cosmochimica Acta*, 51, 2931-2946.

637 Lejeune, A.M., Richet, P. (1995) Rheology of crystal-bearing silicate melts: an experimental study at
638 high viscosities. *Journal of Geophysical Research*, 100, 4215-4229.

639 Le Losq, C., Neuville, D.R., Moretti, R., and Roux, J. (2012) Determination of water content in silicate
640 glasses using Raman spectrometry: implications for the study of explosive volcanism. *American*
641 *Mineralogist*, 97, 779-790.

642 Loomis, A.A. (1963) Noritic anorthositc bodies in the Sierra Nevada Batholith. *Mineralogical Society*
643 *of America Special Paper*, 1, 62-68.

644 Malfait, W.J., Seifert, R., Petitgirard, S., Perrillat, J.-P., Mezouar, M., Ota, T., Nakamura, E., Lerch, P.,
645 and Sanchez-Valle, C. (2014) Supervolcano eruptions driven by melt buoyancy in large silicic
646 magma chambers. *Nature Geoscience*, 7, 122-125.

647 Mao, H.K., and Bell, P.M. (1971) Behavior of thermo-couples in the single-stage piston-cylinder
648 apparatus. *Carnegie Institution of Washington Yearbook*, 691, 207-216.

649 McByrne, A.R., and Murase, T. (1984) Rheological properties of magmas. *Annual Reviews of Earth*
650 *and Planetary Science*, 12, 337-357.

651 McDade, P., Wood, B.J., van Westrenen, W., Brooker, R.A., Gudmudsson, G., Soulard, H., Najorka, J.,
652 and Blundy, J.D. (2002) Pressure corrections for a selection of piston-cylinder cell assemblies.
653 *Mineralogical Magazine*, 66, 1021-1028.

654 Merrill, R.B., and Wyllie, P.J. (1975) Kaersutite and kaersutite eclogite from Kakanui, New Zealand:
655 water excess and water deficient melting to 30 kilobars. *Geological Society of American Bulletin*,
656 86, 555-570.

657 Moore, J.G., and Lockwood, J.P. (1973) Origin of comb layering and orbicular structure, Sierra Nevada
658 Batholith, California. *Geological Society of American Bulletin*, 84, 1-20.

659 Murphy, M.D., Sparks, R.S.J., Barclay, J., Carroll, M.R., Brewer, T.S. (2000) Remobilization of
660 andesite magma by intrusion of mafic magma at the Soufriere Hills Volcano, Montserrat, West
661 Indies. *Journal of Petrology*, 41, 21-42.

662 Ni, H., and Zhang, Y. (2008) H₂O diffusion models in rhyolitic melt with new high pressure data.
663 *Chemical Geology*, 250, 68-78.

664 Ochs, F.A., and Lange, R.A. (1999) The density of hydrous magmatic liquids. *Science*, 283, 1314-
665 1317.

666 Parmigiani, A., Huber, C., and Bachmann, O. (2014) Mush microphysics and the reactivation of
667 crystal-rich magma reservoirs. *Journal of Geophysical Research*, 119, doi:10.1002/2014JB011124.

668 Parmigiani, A., Faroughi S, Huber, C., Bachmann, O., and Su, Y. (2016) Bubble accumulation and its
669 role in the evolution of magma reservoirs in the upper crust. *Nature*, 532, 492-495.

670 Paterson, S.R., Okaya, D., Memeti, V., Economos, R., and Miller, R.B. (2011) Magma addition and
671 flux calculations of incrementally constructed magma chambers in continental margin arcs:
672 combined field, geochronologic, and thermal modeling studies. *Geosphere*, 7, 1439-1468.

673 Paterson, S.R., and Ducea, M.N. (2015) Arc Magmatic Tempos. *Elements*, 11, 155 pp.

674 Petford, N. (2003) Rheology of granitic magmas during ascent and emplacement. *Annual Reviews of*
675 *Fluid Mechanics*, 31, 399-427.

676 Plank, T., Kelley, K.A., Zimmer, M.M., Hauri, E.H., and Wallace, P.J. (2013) Why do mafic arc
677 magmas contain ~4 wt% water on average? *Earth and Planetary Science Letters*, 364, 168-179.

678 Pistone, M., Caricchi, L., Ulmer, P., Burlini, L., Ardia, P., Reusser, E., Marone, F., and Arbaret, L.
679 (2012) Deformation experiments of bubble- and crystal-bearing magmas: rheological and
680 microstructural analysis. *Journal of Geophysical Research*, 117, doi:10.1029/2011JB008986.

681 Pistone, M., Caricchi, L., Ulmer, P., Reusser, E., and Ardia, P. (2013) Rheology of volatile-bearing
682 crystal mushes: mobilization vs. viscous death. *Chemical Geology*, 345, 16-39.

683 Pistone, M., Arzilli, F., Dobson, K.J., Cordonnier, B., Reusser, E., Ulmer, P., Marone, F., Whittington,
684 A.G., Mancini, L., Fife, J.L., and Blundy, J.D. (2015) Gas-driven filter pressing in magmas: insights
685 into in-situ melt segregation from crystal mushes. *Geology*, 43, 699-702.

686 Pistone, M., Blundy, J.D., Brooker, R.A., and EIMF (2016) Textural and chemical consequences of
687 interaction between hydrous mafic and felsic magmas: an experimental study. *Contributions to*
688 *Mineralogy and Petrology*, 171, doi10.1007/s00410-015-1218-4.

689 Podladchikov, Y.Y., and Wickham, M. (1994) Crystallization of hydrous magmas: calculations of
690 associated thermal effects, volatile fluxes, and isotopic alteration. *Journal of Geology*, 102, 25-45.

691 Poldervaart, A., and Taubeneck, W.H. (1959) Layered intrusions of the Willow Lake type. *Geological*
692 *Society of American Bulletin*, 70, 1395-1398.

693 Poli, S., and Schmidt, M.W. (1995) H₂O transport and release in subduction zones: experimental
694 constraints on basaltic and andesitic systems. *Journal of Geophysical Research*, 100, 22299-22314.

695 Romine, W.L., Whittington, A.G., Nabelek, P.I., Hofmeister, A.M. (2012) Thermal diffusivity of
696 rhyolitic glasses and melts: effects of temperature, crystals and dissolved water. *Bulletin of*
697 *Volcanology*, 74, 2273-2287.

698 Saunders, K.E., Buse, B., Kilburn, M., Kearns, S., Blundy, J.D. (2014) Nanoscale characterisation of
699 crystal zoning. *Chem Geology*, 364, 20-32.

700 Schmidt, M.W., Poli, S. (1998) Experimentally based water budgets for dehydrating slabs and
701 consequences for arc magma generation. *Earth and Planetary Science Letters*, 163, 361-379.

702 Seaman, S.J., and Ramsey, P.C. (1992) Effects of magma mingling in the granites of Mount Desert
703 Island, Maine. *Journal of Geology*, 100, 395-409.

704 Shannon, J.R., Walker, B.M., Carten, R.B., and Geraghty, E.P. (1982) Unidirectional solidification
705 textures and their significance in determining relative ages of intrusions at the Henderson Mine,
706 Colorado. *Geology*, 10, 293-297.

707 Sigmundsson, F., Hreinsdóttir, S., Hooper, A., Árnadóttir, T., Pedersen, R., Roberts, M.J., Óskarsson,
 708 N., Auriac, A., Decriem, J., Einarsson, P., Geirsson, H., Hensch, M., Ófeigsson, B.G., Sturkell, E.,
 709 Sveinbjörnsson, H., and Feigl, K.L. (2010) Intrusion triggering of the 2010 Eyjafjallajökull
 710 explosive eruption. *Nature*, 468, 426-430.

711 Sisson, T.W., Grove, T.L., and Coleman D.S. (1996) Hornblende gabbro sill complex at Onion Valley,
 712 California, and a mixing origin for the Sierra Nevada batholith. *Contributions to Mineralogy and*
 713 *Petrology*, 126, 81-108.

714 Sisson, T.W., and Bacon, C.R. (1999) Gas-driven filter pressing in magmas. *Geology*, 27, 613-616.

715 Solano, J.M.S., Jackson, M.D., Sparks, R.S.J., Blundy, J.D., and Annen, C. (2012) Melt segregation in
 716 deep crustal hot zones: a mechanism for chemical differentiation, crustal assimilation and the
 717 formation of evolved magmas. *Journal of Petrology*, 53, 1999-2026.

718 Suzuki, Y., and Nakada, S. (2007) Remobilization of highly crystalline felsic magma by injection of
 719 mafic magma: constraints from the middle sixth century eruption at Haruna Volcano, Honshu,
 720 Japan. *Journal of Petrology*, 48, 1543-1567.

721 Takahashi, N., Kodaira, S., Klemperer, S.L., Tatsumi, Y., Kaneda, Y., and Suyehiro, K. (2007) Crustal
 722 structure and evolution of the Mariana intra-oceanic island arc. *Geology*, 35, 203-206.

723 Tapster, S., Condon, D.J., Naden, J., Noble, S.R., Petterson, M.G., Roberts, N.M.W., Saunders, A.D.,
 724 and Smith, D.J. (2016) Rapid thermal rejuvenation of high-crystallinity magma linked to porphyry
 725 copper deposit formation; evidence from the Koloula Porphyry Prospect, Solomon Islands. *Earth*
 726 *and Planetary Science Letters*, 442, 206-217.

727 Tatsumi, Y. (2000) Continental crust formation by crustal delamination in subduction zones and
 728 complementary accumulation of the enriched mantle component in the mantle. *Geochemistry,*
 729 *Geophysics, Geosystems*, 1, doi:10.1029/2000GC000094.

730 Tomiya, A., Miyagi, I., Saito, G., and Geshi, N. (2013) Short time scales of magma-mixing processes
 731 prior to the 2011 eruption of Shinmoedake volcano, Kirishima volcanic group, Japan. *Bulletin of*
 732 *Volcanology*, 7, 750-768.

733 Trigila, R., Battaglia, M., Sottili, G., and Brilli, M. (2008) Volcanic eruptions from ghost magma
 734 chambers. *Geophysical Research Letters*, 35, doi:10.1029/2008GL034579.

735 Tuttle, O.F., and Bowen, N.L. (1958) Origin of granite in the light of experimental studies in the
 736 system NaAlSi₃O₈-KAlSi₃O₈-SiO₂-H₂O. *Geological Society of America Memoire*, 74, 153 pp.

- Ulmer, P. (1988) High Pressure Phase Equilibria of a calc-alkaline micro-basalt: implications for the genesis of calc-alkaline magmas. *Carnegie Institution of Washington Yearbook, Annual Report of the Director of the Geophysical Laboratory*, 88, 28-35.
- Ulmer, P. (2001) Partial melting in the mantle wedge: the role of H₂O in the genesis of mantle-derived "arc-related" magmas. *Physics and Earth Planetary Interiors*, 127, 215-232.
- Ulmer, P. (2007) Differentiation of mantle-derived calc-alkaline magmas at mid to lower crustal levels: experimental and petrologic constraints. *Periodico di Mineralogia*, 76, 309-325.
- Ulmer, P., Callegari, E., and Sonderegger, U.C. (1983) Genesis of the mafic rocks and their genetical relations to the tonalitic-trondhjemitic granitoids of the southern part of the Adamello Batholith (Northern Italy). *Memorie della Società Geologica Italiana*, 26, 171-222.
- Ulmer, P., and Trommsdorff, V. (1995) Serpentine stability to mantle depth and subduction related magmatism. *Science*, 268, 858-861.
- van der Laan, S.R., and Wyllie, P.J. (1993) Experimental interaction of granitic and basaltic magmas and implications for mafic enclaves. *Journal of Petrology*, 34, 491-517.
- Verberne, R., Ulmer, P., and Müntener, O. (2011) Field relations and consequences for emplacement of the Listino Ring Structure, Adamello Massif, N-Italy, Abstract Volume 9th Swiss Geoscience Meeting.
- Watson, E.B. (1982) Basaltic contamination by continental crust: some experiments and models. *Contributions to Mineralogy and Petrology*, 80, 73-87.
- Yoder, H.S.Jr., and Tilley, C.E. (1962) Origin of basalt magmas: an experimental study of natural and synthetic rock systems. *Journal of Petrology* 3, 342-532.
- Yoder, H.S. Jr. (1973) Contemporaneous basaltic and rhyolitic magmas. *American Mineralogist*, 58, 153-171.
- Yoder, H.S. Jr., Stewart, D.B., and Smith, J.R. (1957) Ternary feldspars. *Carnegie Institution of Washington Year book*, 55, 206-214.

FIGURES

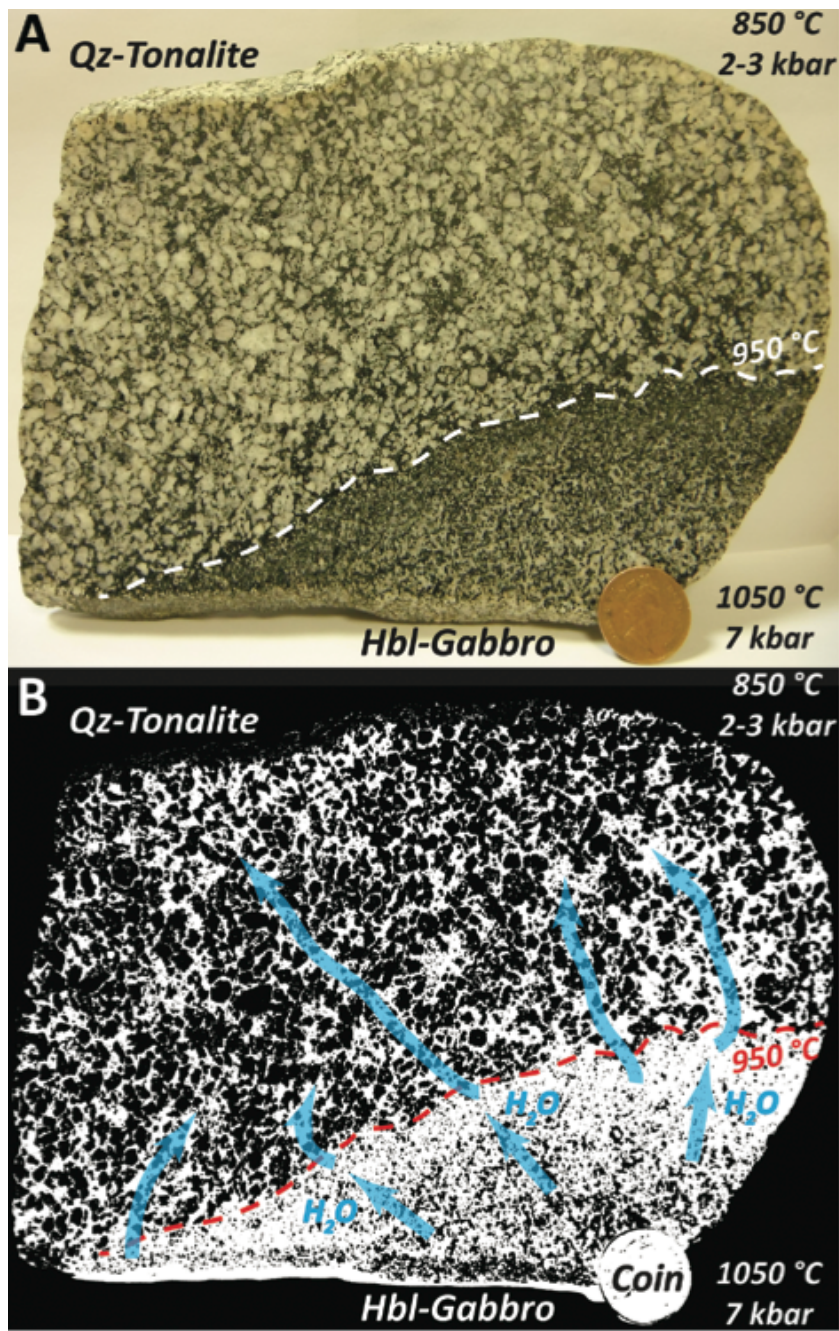


Figure 1: Example of textures associated with hydrous mafic magmas from the Tertiary Adamello Batholith (Alps, Italy). A) Polished rock slab from the Val Fredda Complex (Blundy and Sparks 1992) showing interaction between a hot (1050 °C) hornblende-rich gabbro (lower dark portion) ascending from the deep crust (7 kbar; Ulmer 1988; 2007; Ulmer et al. 1983) and relatively cool (850 °C), partially molten, tonalite host (upper lighter portion) emplaced at shallow depth (2-3 kbar; Blundy and Sparks 1992). The interaction between the two rocks is marked by a fine-grained “chilled margin” to the gabbro at 950 °C (i.e., equilibrium temperature after heat diffusion). Wisps of solidified mafic magma can be seen rising from the interface and permeating the tonalite, which is rendered

773 anomalously darker as a consequence. Rounded, grey quartz phenocrysts in the tonalite have developed
774 hornblende-bearing coronas as a consequence of interaction with mafic magma. The white dashed line
775 outlines the contact between tonalite and gabbro. B) Binary image of the polished rock slab in A
776 showing original whitish minerals in black (i.e., quartz in tonalite and plagioclase in gabbro) and
777 dark/green hornblende in white. The binary image is obtained using the open-source Java image
778 processing software ImageJ v1.4. Light blue thick arrows highlight potential water movement by
779 diffusion and/or exsolution from gabbro to tonalite as revealed by green hornblende in A (white
780 minerals in tonalite in B) and quartz crystal size reduction in the tonalite portions characterised by
781 abundant hornblende. The red dashed line outlines the contact between tonalite and gabbro.

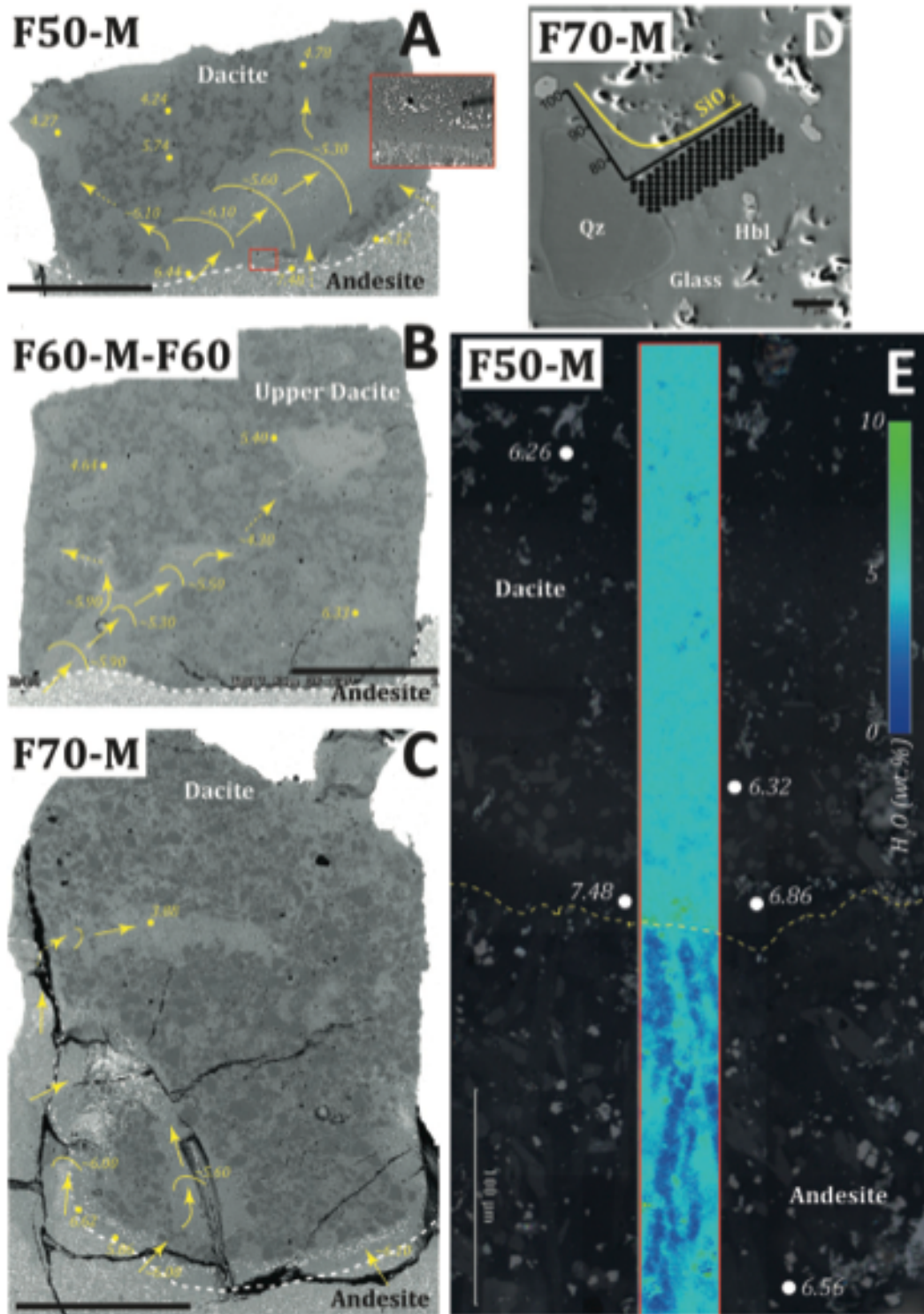


Figure 2: Microstructural and chemical (i.e., H₂O content in the glass) characterisation of experimental run products. **A-C)** BSE image detailing the sample-sample interaction interface of the run products: **A)** F50-M (Setup A); **B)** F60-M-F60 (Setup B); **C)** F70-M (Setup A). The yellow solid (i.e., data-supported) and dashed (i.e., interpreted) arrows indicate directions of H₂O movement in the dacite domain; SIMS-based H₂O content values (in yellow) are in wt% and refer to single analytical spots and

788 average of two or more data analysis spots in the same sample location (highlighted by the curved
789 yellow lines). The white dashed lines show the sample-sample interface. The black scale bar is 1 mm.
790 The red square highlights the image inset in A. **D)** BSE image showing representative FEG-EPMA-
791 based analysis spots (black dots) reporting SiO₂ content across quartz crystal and surrounding glass in
792 run product F70-M. The black scale bar is 7 µm. **E)** Raman-based OH-intensity map, acquired in the
793 range of 1384 to 1412 cm⁻¹, showing H₂O contents in run product F50-M. The white scale bar is 100
794 µm in **E**. The colour scale in **E**, calibrated with SIMS-based H₂O contents in the residual glass (see
795 white dots with corresponding local H₂O contents), shows H₂O content values in wt%. The yellow
796 dashed line in **E** highlights the sample-sample interface. In all panels **A-E** the following phases are
797 present: vesicles (black circles), hornblende (very light grey objects in M and white objects close to
798 quartz crystals in F50), plagioclase (light grey), oxides (white), quartz (very dark grey), and silicic
799 glass (dark grey matrix).

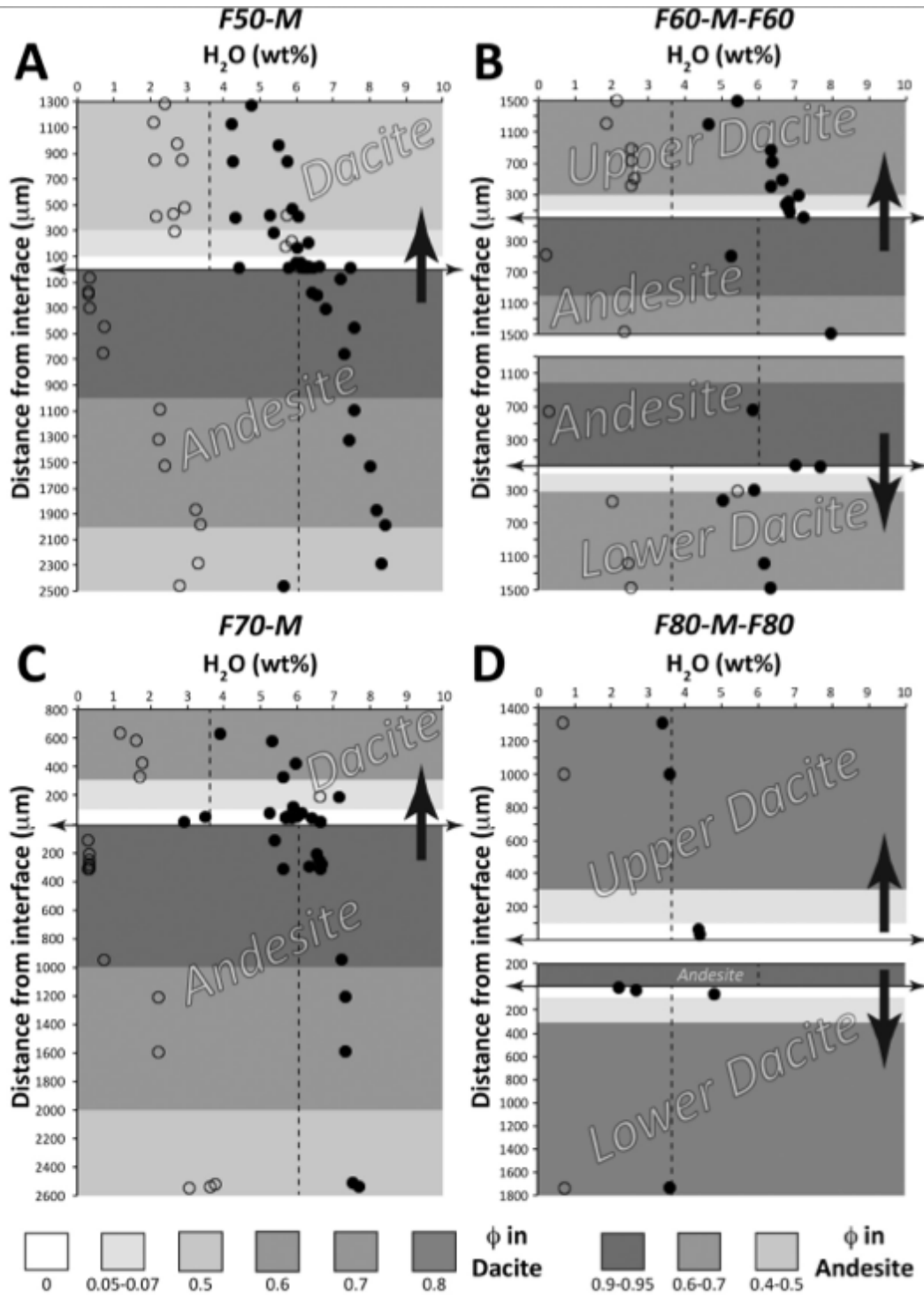
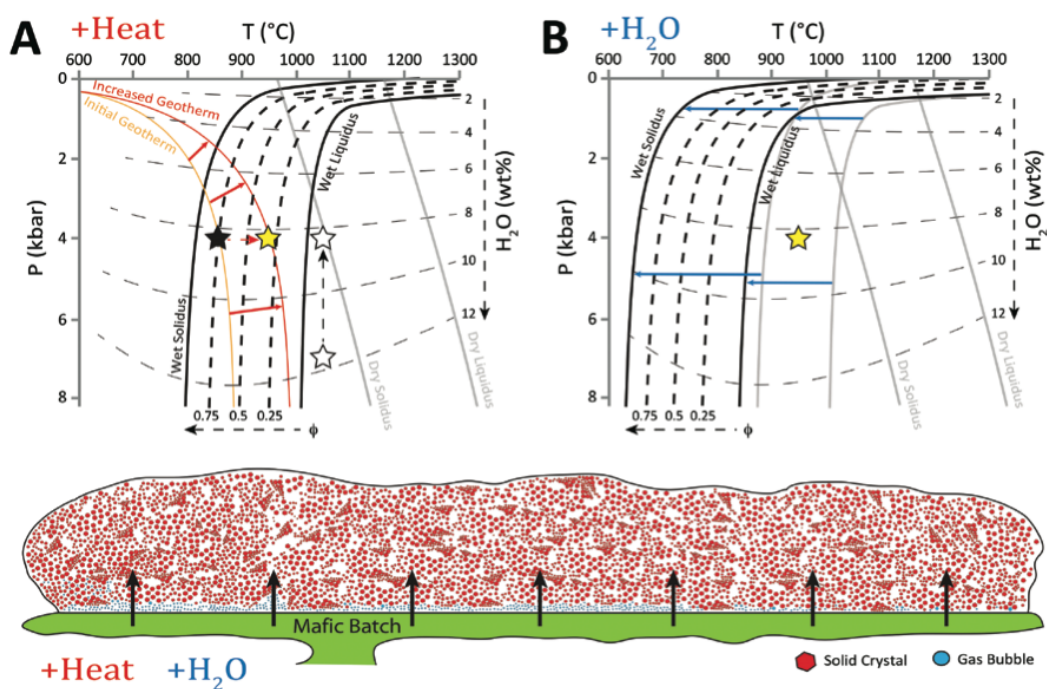


Figure 3: SIMS-based H₂O contents in the interstitial glass (black circles) and calculated bulk H₂O (open circles) across different run products. Data are displayed according to the orthogonal distance of the analysis spots from the interface(s) between samples (displayed as horizontal black solid lines with opposing arrows). Vertical black dashed lines represent starting H₂O contents in the glass of dacite and andesite samples. Grey scale areas indicate different crystal fractions (ϕ ; darker area = larger

806 crystallinity) in dacite and andesite. Large black solid arrows indicate directions of H₂O movement
 807 during interaction.

808

809



810

811 **Figure 4:** Pressure-temperature plot showing H₂O-saturated (wet) liquidus and solidus temperatures
 812 (black solid curves) and contours of H₂O solubility increasing with pressure/depth (dashed lines) in
 813 haplogranite melts based on the experimental data of [Holtz et al. \(1995\)](#) and the phase relation
 814 calculations of [Holland and Powell \(2001\)](#). Despite the compositional differences between haplogranite
 815 ([Holtz et al. 1995](#)) and rhyolite melts (this study), this diagram can be applied generally to high-silica
 816 systems (> 65 wt% SiO₂). This plot illustrates the effect of coupled heat and water diffusion from the
 817 hot (1050 °C) crystal-poor gabbroic magma (white star), ascending adiabatically from the deep crust (7
 818 kbar; [Ulmer 1988; 2007; Ulmer et al. 1983](#)) into the original crystal-rich (> 70 vol% crystals) host
 819 tonalite (850 °C; 4 kbar, based on the experiments of this study; black star). The mafic-felsic
 820 interaction heats the tonalite system to increase to 950 °C (yellow star; [Blundy and Sparks 1992](#)) and
 821 drives partial melting by heat diffusion (A). The addition of H₂O suppresses the liquidus and solidus
 822 temperature (i.e., liquidus temperature down to 800 °C, with an average value of 860 °C; [Pistone et al.](#)
 823 [2016](#)), further increasing the melting of the tonalite under isothermal conditions (B). Thick dashed lines
 824 depict different crystal fractions (ϕ) of the host tonalite. H₂O-free (dry) liquidi and solidi are reported

for reference. The mafic magma (white star) is reported in A for reference; but this composition is characterised by different phase relations, including liquid and solid, which are not shown here. The qualitative sketch (redrawn after [Pistone et al. 2013](#)) shows an upper crystal-rich felsic pluton underplated by a hot mafic magma releasing heat and water into the felsic host (see black arrows). In this sketch gas exsolution is expected at the interface when the residual melt is H₂O-saturated as observed in the run products (see inset image in Figure 2A).

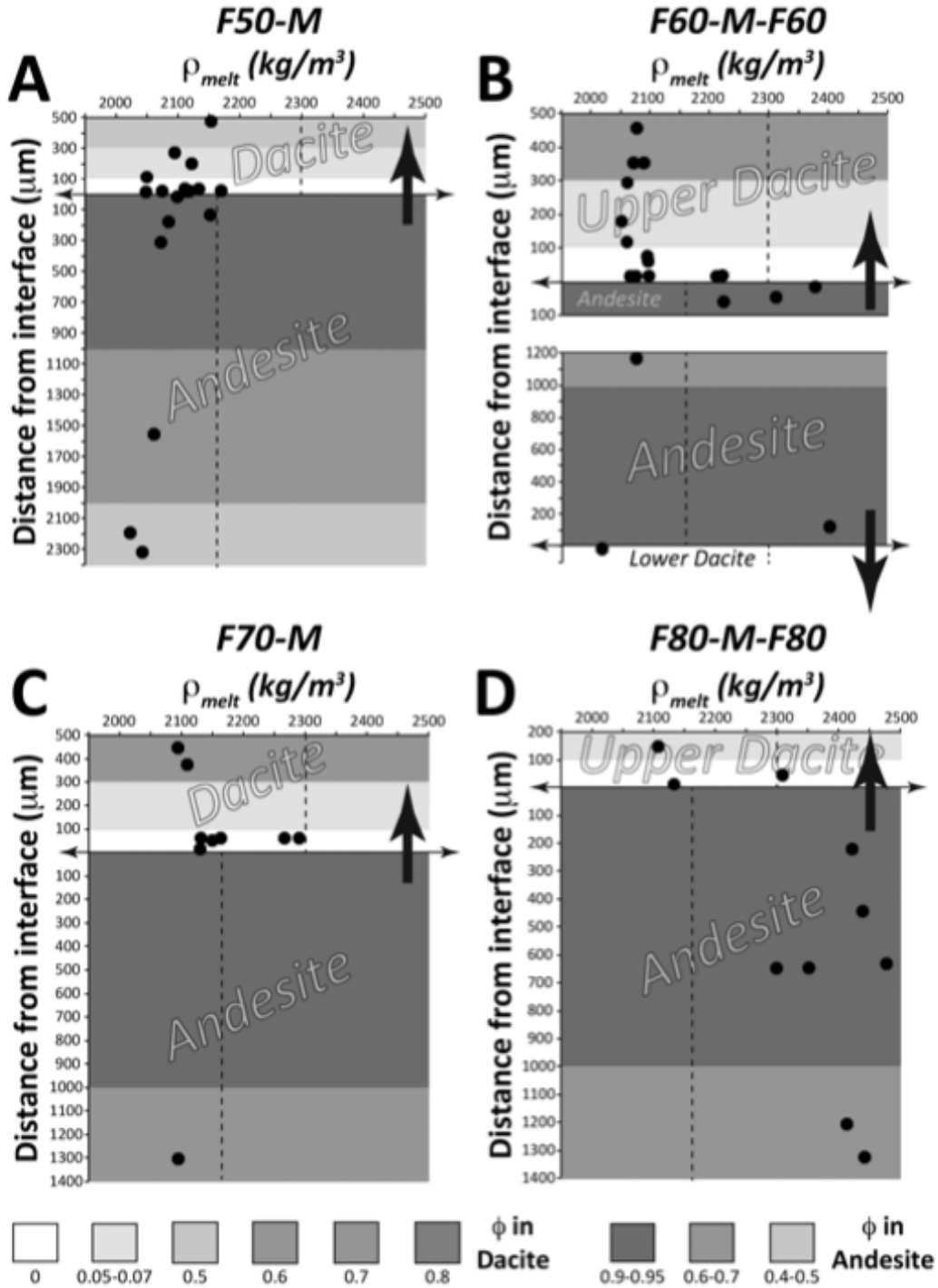


Figure 5: Melt density (ρ_{melt}) profiles within the experimental charges from this study. ρ_{melt} values of the residual glass in the dacite and andesite were estimated using a combination of EPMA-based glass chemistry, SIMS-based H₂O data and the model of [Lange and Carmichael \(1987\)](#). Crystal fraction values and symbols as in Figure 2.

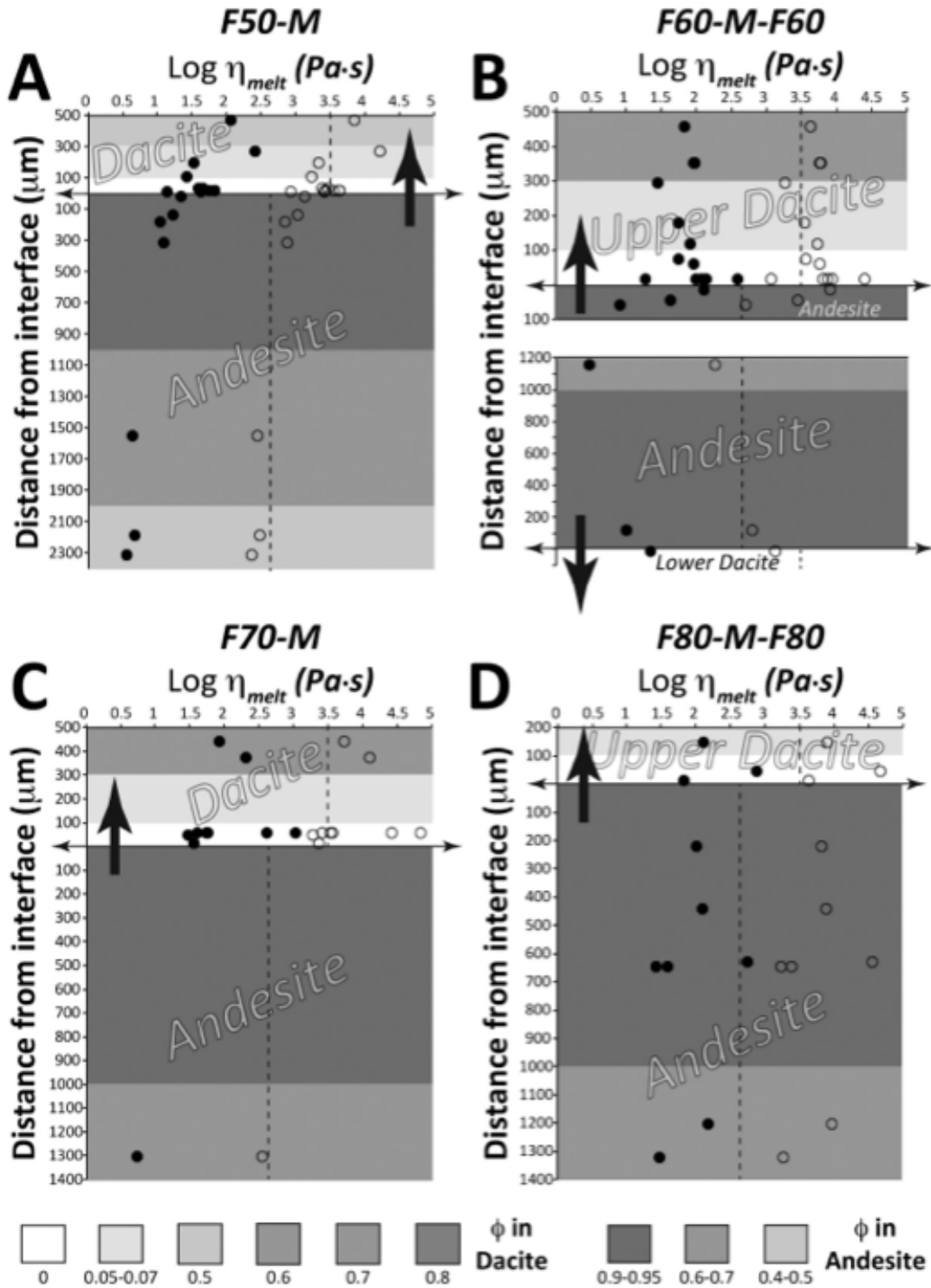
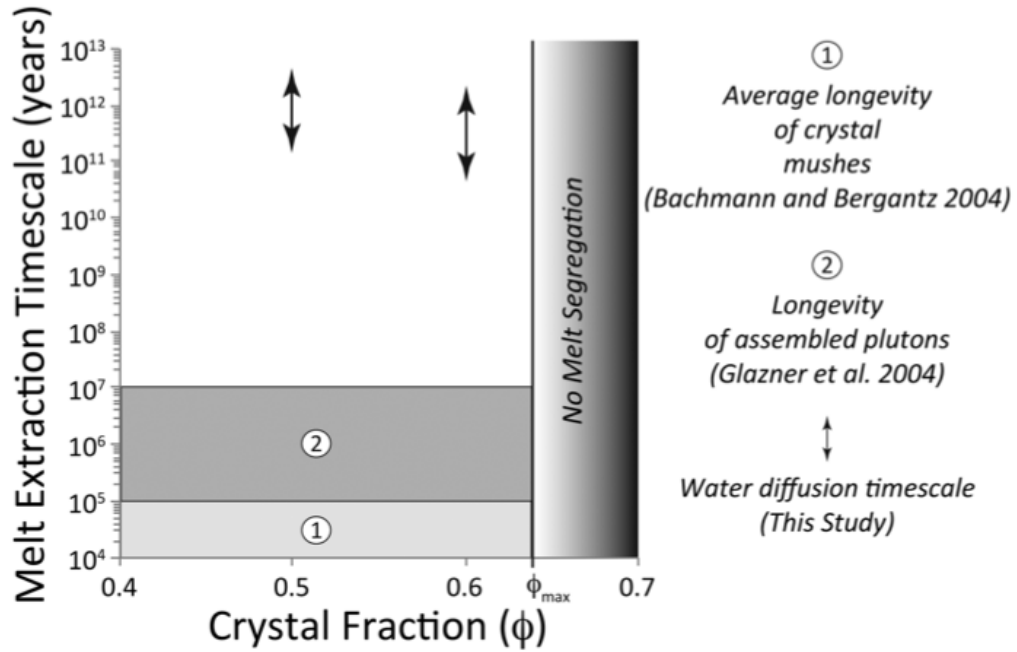


Figure 6: Logarithm of melt viscosity (η_{melt}) profiles within the experimental charges from this study. η_{melt} values of the residual glass in the dacite and andesite were estimated using a combination of the EPMA-based glass chemistry, SIMS-based H_2O data and the model of [Giordano et al. \(2008\)](#), which is calibrated at 1 bar (black circles). A correction factor of 1.8 log units in η_{melt} due to the pressure effect

843 on η_{melt} (Ardia et al. 2008; 2014; Pistone et al. 2012; $P\text{-}\eta_{melt}$) is applied (open circles). Crystal fraction
 844 values and symbols as in Figure 2.
 845
 846



847
 848 **Figure 7:** Log-time required to extract silicic melt from a crystal mush a function of crystal fraction
 849 (ϕ). The light and dark grey rectangles indicate the average residence times of crystal mushes (10^4 - 10^5
 850 years; Bachmann and Bergantz 2004, and references therein) and those of long-lived plutons in the
 851 Earth's crust (Glazner et al. 2004). Water diffusion timescale (see double arrows) is calculated using
 852 the simple approximation: $x=t \times DH_2O$, (Watson 1982; Baker 1991; with $DH_2O = 3 \cdot 10^{-10} \text{ m}^2/\text{s}$; Ni
 853 and Zhang (2008), and t = experimental duration), a length scale ranging from 5 to 25 m based on the
 854 length scale of the leucogranite dikes (i.e., extracted melt from the Monoccola Granodiorite mush)
 855 observed in the Listino Ring Complex in Adamello Massif, Italy (Verberne et al. 2011). Above the
 856 crystal maximum packing fraction ($\phi_{max} = 0.64$), melt extraction ceases.